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Less Efficient Elementary Visuomotor Processes in 7- to 10-Year-Old Preterm-Born Children Without Cerebral Palsy: An Indication of Impaired Dorsal Stream Processes

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Follow-up studies of preterm children without serious neurological complications have consistently found deficits in visuomotor skills. To determine whether these deficits may be related to impaired elementary visuomotor processes, we investigated movement programming and execution of simple pointing movements in 7- to 10-year-old preterm (<34 weeks g.a. and/or b.w. <1800 g) and full-term children. Such detailed analysis of simple pointing movements provides information on the extent to which processes associated with dorsal and/or cerebellar functions are impaired. Multi-level analysis showed that movement programming and execution were slowed in the 7-, 9-, and 10-year-old preterm groups. This indicates impaired dorsal visual stream functioning in preterm children, but do not rule out impaired cerebellar functioning. At 8 years of age, there were no differences between the two groups in movement execution time. This could have reflected a transition in the development of movement control in the control group, which has been associated in typically developing children with a decrease in motor speed. Interestingly, a similar decrease was not found in the preterm group at 8 years of age.

Keywords: pointing movement, kinematic characteristics, movement control, dorsal visual stream, cerebellum

As a result of improved care in the last few decades, an increasing number of children survive preterm birth without serious neonatal medical complications (Lemons et al., 2001). Research into the long-term consequences of preterm birth in this group has focused on the more subtle signs of impairment (Foreman, Fielder, Minshell, Hurrion, & Sergienko, 1997; Lukeman & Melvin, 1993). Follow-up studies report lower intelligence scores, learning difficulties, behavioral problems, and mild motor problems (for intelligence scores, see Caravale & Vicari, 2004; Luoma, Herrgård, & Martikainen, 1998; Pinto-Martin, Whitaker, Feldman, Van Rossem, & Paneth, 1999; for learning difficulties, see Saigal et al., 2003; Schothorst & van Engeland, 1996; for behavioral problems, see Schothorst & van Engeland, 1996; Torrioli et al., 2000; for motor problems, see Holsti, Grunau, & Whitfield, 2002; Jongmans, Mercuri, de Vries, Dubowitz, & Henderson, 1997). These subtle impairments may interfere with preterm-born children's daily life.

One of the more consistent findings in follow-up studies of preterm-born children is a deficit in visuomotor and visuospatial skills (Caravale & Vicari, 2004; Goyen, Lui, Woods, 1998; Jongmans et al., 1997; Luoma et al., 1998; van den Hout et al., 2000), which has been hypothesized to reflect impaired dorsal stream functioning (Foreman et al., 1997). Ventral visual stream functioning, in contrast, seems to be relatively intact. Aspects of object perception associated with the ventral stream, for example, show less (Luoma et al., 1998) or no impairment (Foreman et al., 1997; Goyen et al., 1998), although aspects not associated with the ventral stream, for example, recognition of objects from unconventional viewpoints, may be specifically impaired (Van den Hout et al., 2000).

Milner and Goodale (1995) have redefined the functions of the ventral and dorsal streams identified by Ungerleider and Mishkin (1982) on the basis of how each stream processes spatial information. They argue that the ventral stream processes visual information for object recognition using multiple frames of reference ("what" stream), whereas the dorsal stream processes visual information for fast goal-directed action such as reaching and grasping

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using an egocentric frame of reference ("how" stream; for review, see Creem & Proffitt, 2001). The distinction between "vision for perception" and "vision for action" was based on evidence from neurological patients (Goodale, Westwood, & Milner, 2004; James, Culham, Humphrey, Milner, & Goodale, 2003) and normal participants (for review, see Carey, 2001).

Evidence from imaging studies is consistent with an impairment of the dorsal visual stream in preterm-born children without serious neonatal medical complications. At 40 weeks gestational age, diffusion tensor imaging (DTI) has shown that white matter fibers in areas of the brain through which the dorsal stream flows are shorter, thinner, and less organized in preterm than full-term control infants (Hüppi et al., 1998). At 11 years of age, DTI has suggested reduced thickness, fewer axons, and/or poorer myelination of the white matter in these brain areas in preterm than in full-term control children (Nagy et al., 2003).

Until now, visuomotor functioning in preterm-born children generally has been investigated using complex visuomotor tests, such as Beery′s Developmental Visual–Motor Integration test (VMI), the Rey–Osterrieth Complex Figure test (ROCF), and the NEPSY (for VMI: Caravale & Vicari, 2004; Jongmans et al., 1997; Torrioli et al., 2000; Waber & McCormick, 1995; for ROCF: Waber & McCormick, 1995; for NEPSY: Herrgård, Luoma, Tuppurainen, Karjalainen, & Martikainen, 1993; Luoma et al., 1998). Such tests provide little insight into the elementary visuomotor processes associated with the dorsal stream. The only exception, to our knowledge, is an investigation, by Foreman et al. (1997), using a pointing task. Numerous studies have shown that pointing tasks are rigorous tests of dorsal stream functioning (for review in monkeys, see Jeannerod, 1997; in humans, see Rossetti & Pisella, 2002). Foreman et al. found that response times—movement programming plus execution time—were longer in 6-year-old preterm-born children than in full-term controls. They concluded that the reduced efficiency of these elementary visuomotor processes could reflect impaired dorsal visual stream functioning.

However, pointing tasks involve both the rapid transformation of visual information into motor parameters, a dorsal stream function (Milner & Goodale, 1995), and online comparison of feedback sensory information with the efference copy or feedforward model of the sensory consequences of the movement, which is a cerebellar function (Blakemore, Frith, & Wolpert, 2001). Thus, longer response times on a pointing task may also reflect impaired cerebellar functioning. Volumetric MRI analyses have shown that cerebellar growth is impeded both at birth (Limperopoulos et al., 2005) and at 14 years of age in preterm- born children (Allin et al., 2001). Impaired cerebellar development in preterm-born infants may be associated with cerebral white matter injury (Shah, Anderson, Carlin, Pavlovic, Howard, et al., 2006).

To investigate whether elementary visuomotor processes are impaired in preterm-born children without serious neonatal medical complications, we compared the programming and execution of rapid, goal-directed pointing movements in preterm-born children (gestational age $<$ 34 weeks or birth weight $<$ 1,800 g) without cerebral palsy and age-matched full-term children. Children ages 7 to 10 years old were selected for study because research into pointing movements has consistently found that movement control develops nonmonotonically in typically developing children, decreasing in efficiency around 8 years of age (Chicoine, Lassonde, & Proteau, 1992; Ferrel, Bard, & Fleury, 2001; Hay, 1979; Pellizzer & Hauert, 1996; van Dellen & Kalverboer, 1984). Around this age, a transition is thought to occur in the processing of visual and proprioceptive information, which is associated with a slowing of fast, visually guided movements with no commensurate gain in endpoint accuracy. Differences between children with and without deficits in a particular skill may differ in size around a transition in the development of that skill. Restricting the sample to a single age group increases the risk that deficits may be overlooked or exaggerated, depending on the phase in the transition. Including a broad age range reduces that risk.

A kinematic analysis of the children's movements allowed us to determine whether processes associated with dorsal and cerebellar functions were impaired. Reaction times on a simple pointing task reflect the duration of the movement programming phase and provide information on the speed of transforming visuospatial information into motor parameters, a dorsal stream function. Given that no sensory feedback processing is involved during this phase, differences in reaction time are unlikely to be related to differences in cerebellar functioning. Movement times provide information on the quality of both movement programming and feedback processing. Rapid, visually guided pointing movements consist of an acceleration phase followed by a deceleration phase. The processing of visual feedback starts at the earliest 100–130 ms after movement onset (for review, see Elliott, Binsted, & Heath, 1999). The acceleration phase is therefore unlikely to reflect differences in the time taken to process visual feedback for movement correction (Darling & Cooke, 1987). Its duration reflects mainly the accuracy of the movement programming phase, and thus provides an estimate of the quality of dorsal stream processing. The involvement of the cerebellum in the acceleration phase is as yet unclear. The duration of the deceleration phase, although primarily determined by movement programming, may be strongly influenced by online correction of the movement program using visual and kinesthetic feedback (Elliott et al., 1999). Consequently, during this last phase both dorsal stream and cerebellar processes are involved. Endpoint accuracy provides a measure of accuracy, allowing differences in speed–accuracy trade-off to be identified.

If the dorsal visual stream is involved in the visuomotor impairment of preterm-born children, both movement programming (reaction time) and execution (movement time, acceleration phase, deceleration phase) should be slower in the preterm group. If the cerebellum but not the dorsal stream is involved, then movement execution, but not movement programming, should be slower in the preterm group. Because the development of movement control in typically developing children has been shown to be nonlinear, any differences between the two groups should differ in strength at different ages. In particular, given that movement control undergoes a transition between 7 and 8 years in typically developing children, any differences in movement execution between the two groups should be less apparent at this age. Finally, to determine whether any slowing in movement programming (reaction time) on the pointing task reflected a general slowing of information processing, we also had the children carry out a visual–perceptual detection task. This control task required the processing of visual information and the execution of a simple movement without transformation of the visual information into movement direction and distance parameters. Thus, a slowing in both reaction time on the pointing task and detection time on the control task would suggest a general slowing in responding, whereas a slowing in reaction time but not in detection time would suggest a slowing in processes limited to the transformation of visual–spatial information for movement programming.

Method

Participants

Participants were 55 preterm-born children (gestational age < 34 weeks or birth weight < 1,800 g) between the ages of 7 and 10 years. The children were part of a group of 82 mainly inborn children, admitted within 24 hr of birth to the Neonatal Intensive Care Unit of the University Medical Center of Groningen between October 1992 and January 1996. At 6 years of age, all children were neurologically examined. Twelve were classified as cerebral palsy (CP). These children were excluded from the study. Five families could not be located at the time of the study. Six families refused to participate. Data were unavailable for 3 children because of technical problems. One child refused to cooperate. Technical problems led to the loss of data on the visual–perceptual detection task for 7 of the remaining 55 preterm-born children.

The perinatal clinical characteristics are presented in Table 1. At the time of the study, all children were neurologically reexamined. None were classified as CP. All children had corrected vision when required. None were diagnosed with low vision, as defined by the World Health Organization (<10 c/deg). More sample characteristics are presented in Table 2.

Forty-five full-term children between 7 and 10 years of age took part in the study. All full-term children were recruited through mainstream elementary schools in and around Groningen, and all had uneventful pre- and perinatal histories. Mean gestational age was 40w2d (range 37w0d–42w0d). Mean birth weight was 3,613 g (range 2,580 g–4,949 g). The full-term group was selected to be similar to the preterm group on gender, hand preference, and age, the characteristics most likely to influence performance on a simple pointing task (see Table 2). The full-term group was also selected to be similar to the general population in performance on the Movement ABC (M-ABC; Smits-Engelsman, 1998): children with a total M-ABC score or a fine motor score ≤ percentile 5 were excluded. Mean total M-ABC score was percentile 45 (range 8–92). In both groups, IQs were assessed using a short form of the Weschler Intelligence Scale for Children—Third Edition (Kort et al., 2002; see Table 2). All children participated within 6 months of their birthday.

The ethical review board of the university medical center approved the research project.

Table 1
Perinatal Clinical Characteristics of the Preterm Group

Characteristic	Preterm group (n = 55)
Mean (range) gestational age	29w6d (25w5d–33w5d)
Mean (range) birth weight (BW)	1,192 g (595g–1,800g)
Boys:girls, *n*	30:25
SGA (BW < percentile 5), *n* (%)	14 (25)
Prenatal corticosteroids, *n* (%)	37 (67)
IPPV, *n* (%)	28 (51)
Septicemia, *n* (%)	20 (36)
ICH Grade 1–2, *n* (%)	11 (20)
ICH Grade 3–4, *n* (%)	0 (0)
PVL Grade 1, *n* (%)	23 (42)
PVL Grade 2–3	0 (0)
Mean (range) NBRS at term age	3 (1–7)
BPD, *n* (%)	14 (25)
Postnatal corticosteroids, *n* (%)	6 (11)
Retinopathy of prematurity, *n* (%)	0 (0)

Note. Data are expressed as mean (minimum – maximum), or *n/N* (%). SGA = small for gestational age, according to the Dutch weight centiles of Kloosterman (1970); IPPV = intermittent positive pressure ventilation; ICH = intracranial haemorrhage, graded according to Papile, Burstein, Burstein, and Koffler (1978); PVL = periventricular leukomalacia, graded according to de Vries et al. (1992); NBRS = nursery neurobiologic risk score, i.e., a neonatal risk score (Brazy Eckerman, Oehler, Goldstein, & O'Rand, 1991); BPD = bronchopulmonary dysplasia, defined as oxygen dependency at 36 weeks postmenstrual age.

Table 2
Sample Characteristics for Each Age Group and IQs for the Full-Term and Preterm-Born Children

Characteristic	Full term	Preterm
7 years		
Mean (*SD*) age	7y4m (1m)	7y4m (1m)
Boys:girls, *n*	2:8	3:9
Left:right hand preference, *n*	3:7	3:9
8 years		
Mean (*SD*) age	8y4m (1m)	8y4m (2m)
Boys:girls, *n*	8:5	12:5
Left:right hand preference, *n*	4:9	6:11
9 years		
Mean (*SD*) age	9y4m (1m)	9y4m (2m)
Boys:girls, *n*	11:5	9:8
Left:right hand preference, *n*	2:14	1:16
10 years		
Mean (*SD*) age	10y4m (1m)	10y4m (1m)
Boys:girls, *n*	4:2	6:3
Left:right hand preference, *n*	0:6	0:9
All		
Mean (*SD*) total IQ	105 (8)	95 (9)
Mean (*SD*) verbal IQ	107 (9)	94 (9)
Mean (*SD*) performance IQ	103 (11)	95 (11)

Apparatus

The children carried out the tasks seated in front of a touch-screen, which was tilted at an angle of 15° from the horizontal. The borders of the monitor and the table were matched to the color of the computer screen. All movements were made with the dominant hand. The participant's sitting height could be adjusted so that the elbow and forearm rested comfortably on a support while the index finger rested on a finger key in front of, and aligned with the center of, the touch-screen (see Figure 1). An infrared reflecting marker was attached to the nail of the index finger. The movement of the marker was registered with a frequency of 100Hz by three infrared cameras (PRIMAS) suspended in a shallow arc above the touch-screen. The child's face and the display on the touch-screen were shown on an SVHS-video monitor, allowing one experimenter to present the target only when the child was looking at the touch-screen. A second experimenter stood behind the child to ensure

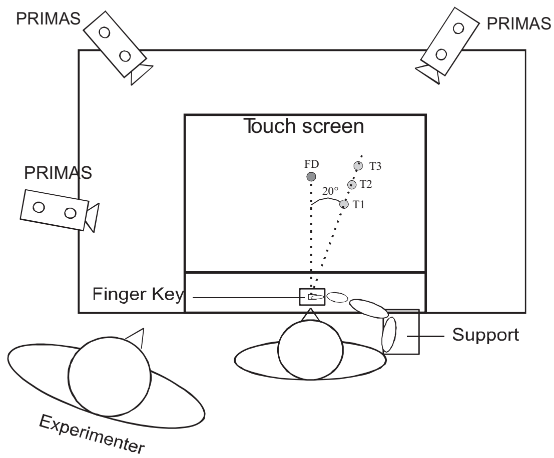

Figure 1. View from above of the position of participant, experimenter, and equipment, and of target positions on touch-screen for right-handed participants. FD = fixation dot; T1–T3 = Target 1–Target 3.

that the hand and arm were in the required position at the beginning of each trial and that the child was attending to the task.

Procedure

Pointing task. The child started each trial by depressing the *finger* key. A colored picture appeared in the upper left corner of the touch-screen. Next, a red fixation spot (7.5 mm ∅) appeared at the vertical midline of the screen at a distance of 60% of the average arm length of the age group concerned (24 cm in 7- and 8-year-old children, and 26.5 cm in 9- and 10-year old children, according to Gerver & de Bruin, 2001). After a variable fixation interval (500–3,000 ms), a green target spot (7.5 mm ∅) appeared on the side of the dominant hand at one of three distances along an axis at an eccentricity of 20° from the screen's vertical midline (see Figure 1). The distances were scaled to the average arm length of the age group: near (47.5%), center (60%), or far (72.5%). The center target and the fixation spot were equidistant from the finger key. Ten trials were presented at each target distance in pseudorandom order. The child was instructed to touch the spot with the index finger as quickly and accurately as possible. Accurate touches were rewarded with a short tone.

Visual–perceptual detection task. The child started each trial by depressing the finger key, which he or she then released, leaving the finger resting on the key. The following two steps were similar to those in the pointing task. However, on Step 4, the target was always presented at the same location as the center target on the pointing task. The target remained visible for 3,000 ms on 8 trials (catch trials). On the remaining 16 trials, it disappeared to reappear at the near target location (8 trials) or the far target location (8 trials). To discourage anticipation, on half of the near and far "reappearing target" trials, the target reappeared after 400 ms and on the other half after 800 ms. The five conditions were presented in pseudorandom order. The child was instructed to depress the finger key as soon as the target reappeared on the "reappearing target" trials and to withhold a response on the catch trials.

Each task was preceded by a practice session of five to six trials and took approximately 3 min to complete.

Analysis

Parameter calculation. For the pointing task, we analyzed the data using custom-written software in MATLAB (The MathWorks, 2004), in which the movement, the stimulus, the finger key, and touch-screen data were integrated on a common time scale. Reaction time (RT) was the interval between the presentation of the target stimulus and the release of the finger key. Movement time (MT) was the interval between the release of the finger key and the touch on the screen. Acceleration time (ACCT), the interval between the beginning of the movement and moment of peak velocity, and deceleration time (DECT), the interval between moment of peak velocity and the end of the movement, were calculated from three-dimensional movement trajectories. Pointing error (PE) was calculated using the touch-screen data (resolution of 0.35 mm), and was the absolute distance between the midpoint of the stimulus and the touch on the screen. For the visual–perceptual detection task, detection time (DT) was the time between the presentation of the reappeared target and the depressing of the finger key.

Statistical analysis. Trials on which the child was inattentive or anticipated the stimulus, as assessed by the second experimenter, were excluded from the analyses. Pointing task trials with MTs or RTs more than 3 standard deviations above the child's average were excluded (11 trials in the preterm group, $< 1\%$; 15 trials in the control group, 1%). Detection task trials with DTs shorter than 200 ms and longer than 1,000 ms were also excluded. Because the RTs and DTs in both groups were positively skewed, we carried out the analyses on logarithmic transformations, and back-transformations are reported.

The data were analyzed using multilevel modeling (Snijders & Bosker, 1999) in the statistical program MLwiN 2.00 (Rasbash, Browne, Healy, Cameron, & Charlton, 2004). Here, multilevel analysis allows more accurate statistical testing than the standard repeated measures (multivariate) analysis of variance approach because it allows unequal numbers of observations per individual, and it does not assume equality of group variances (Maas & Snijders, 2003). Two fully multivariate models were specified with trial as a random factor: one model taking the 3 distances $\times$ 10 trials design of the pointing task into account, and another model taking the 2 distances $\times$ 8 trials design of the detection task into account. First, for each movement parameter, we constructed a saturated model with the near target in the 7-year-old control group as the intercept. All terms were a combination of the levels of the factors target distance, age, and clinical status leading to $3 \times 4 \times 2 = 24$ terms in the pointing task and $2 \times 4 \times 2 = 16$ terms in the detection task, respectively (categorical model). Second, to arrive at a parsimonious model, we constructed a second model for each movement parameter on the pointing task, in which target distance was modeled as an interval variable (interval model). This model assumed that the movement parameters differed systematically with target distance. The distance effect was parameterized by replacing the near, center, and far target terms with one variable (target distance) with the respective values of 0, 1, and 2, leading to a model with 16 terms ($2 \times 4 \times 2 =$ intercept and slope of Target

Distance × Age × Clinical Status, respectively). The intercept in the interval model was the near target in the 7-year-old control group. Third, the categorical and interval models for each movement parameter were compared using a deviance test. A deviance test is a likelihood ratio test comparing two "nested" models, and follows a chi-square distribution with degrees of freedom equal to the number of extra parameters in the larger, that is, categorical, model compared with the smaller, that is, interval, model (i.e., $24 - 16 = 8$ *df*s; see Snijders & Bosker, 1999, Ch. 6.2). The best fitting model of each parameter was used in further analysis.

To arrive at a simpler, easier to interpret model, we simplified the best fitting model by removing terms that were not included in a higher order interaction term one by one on the basis of two predefined criteria (backward model selection). The first criterion was that the coefficient of a term did not reach statistical significance ($p > .05$). The second criterion was based on effect size. For the time parameters, we established this criterion using the minimal average lengthening of MT at any age between two target distances in the saturated model, which is not described here. In this model, the 9-year-old control group had the smallest lengthening of MT of 12.6 ms between the near and far targets. To be conservative, we selected a coefficient smaller than 5.5 ms for the center target terms in the categorical model or target distance terms in the interval model as this criterion and a coefficient smaller than 11 ms for the far target terms in the categorical model. For PE, the high measurement accuracy of the touch-screen, which has a resolution of 0.35 mm, resulted in negligible differences between groups. Therefore, we selected a difference of 2 mm as the criterion for PE.

All reported results are based on the simplified models. In the graphs, the near target distance coefficient for each group is displayed. Model-derived means rather than raw means were used as the former takes the differences in numbers of participants per clinical status group and numbers of observations per participant into account. To illustrate how estimates for interaction effects are calculated, we calculate the estimated mean MT of the center target in the 9-year-old preterm group using the model in Table 3: 405.1 (intercept) + 2.7 (9-year-old group) + 63.8 (preterm group) + 0 (Preterm × 9-Year-Old Group) + 18.1 (target distance) − 6.3 (Target Distance × 9-Year-Old Group) + 0 (Target Distance × 9-Year-Old Group × Preterm Group) = 483.4 ms. To test for differences between an estimated mean and the intercept, we used a *t* test (see Snijders & Bosker, 1999, Ch. 6.1). To test for differences between two estimated means, we tested the contrast of the sum of the parameters from which each estimate was derived using a chi-squared test with 1 degree of freedom.

Results

First, we report the results of the comparison of the preterm group with the control group on the pointing task. Results for the movement programming phase and the movement execution phase are presented separately. Then, we report the results of the comparison of the different age groups within the two groups on the pointing task. Only comparisons of consecutive age groups are reported. Finally, we report the results of the comparison of the preterm group and the control group on the visual–perceptual control task. We do not report the results on the effect of target distance because this effect was not included in the hypotheses.

For RT, MT, ACCT, and DECT, the deviance test showed no significant differences ($p > .05$) between the categorical and interval models, which indicates that there is a systematic association between the parameters and target distance, that is, an in-

Table 3
Simplified Interval Models for Reaction Time (RT), Movement Time (MT), Acceleration Time (ACCT), and Deceleration Time (DECT) of the Pointing Task

	RT			MT			ACCT			DECT		
Predictor term	Est. (ms)	*t* ratio	*p*	Est. (ms)	*t* ratio	*p*	Est. (ms)	*t* ratio	*p*	Est. (ms)	*t* ratio	*p*
Intercept	5.838			405.1			155.0			257.5		
Target distance	0.016	0.70	.24	**18.1**	**5.64**	**.000**	**8.8**	**6.71**	**.000**	**9.3**	**2.71**	**.003**
Target Distance × Age 8	0.017	0.55	.29	0.2	0.04	.48	—	—	—	—	—	—
Target Distance × Age 9	−0.028	−0.93	.18	**−6.3**	**−1.64**	**.05**	—	—	—	−6.7	−1.41	.08
Target Distance × Age 10	0.019	−0.50	.31	—	—	—	−3.5	1.02	.15	−0.5	−0.08	.47
Target Distance × Preterm	−0.015	−0.44	.33	−6.1	−1.53	.06	1.2	0.58	.28	1.7	0.32	.37
Target Distance × Age 8 × Preterm	−0.020	−0.43	.33	10.0	1.27	.10	—	—	—	—	—	—
Target Distance × Age 9 × Preterm	0.048	1.06	.14	—	—	—	—	—	—	−10.7	−1.32	.09
Target Distance × Age 10 × Preterm	0.044	0.85	.20	—	—	—	6.2	1.29	.10	−11.5	−1.32	.09
Age 8	**−0.160**	**−1.95**	**.03**	33.1	0.90	.19	**15.8**	**1.69**	**.05**	10.6	0.29	.39
Age 9	**−0.198**	**−2.71**	**.004**	2.7	0.10	.46	—	—		−8.9	−0.26	.40
Age 10	**−0.371**	**−1.91**	**.03**	**−57.2**	**−1.76**	**.04**	**−22.0**	**−1.71**	**.05**	−37.9	−0.87	.19
Preterm	**0.199**	**1.93**	**.03**	**63.8**	**2.68**	**.004**	**21.9**	**2.83**	**.003**	30.0	0.82	.21
Preterm × Age 8	−0.038	−0.23	.41	**−72.5**	**−1.66**	**.05**	−15.4	−1.21	.11	−45.1	−0.95	.17
Preterm × Age 9	−0.020	−0.15	.44	—	—	—	—	—	—	15.2	0.32	.37
Preterm × Age 10	−0.148	−0.62	.27	—	—	—	−7.2	−0.43	.33	14.4	0.25	.40

Note. Values in bold are significant at $p \leq .05$, and the effect size was larger than criterion. Dashes indicate that the term was removed from the model.

Table 4
Simplified Categorical Models for Pointing Error (PE) of the Pointing Task and Detection Time (DT) of the Visual-–Perceptual Control Task

	PE			DT		
Predictor term	Est. (mm)	*t* ratio	*p*	Est. (ms)	*t* ratio	*p*
Intercept	8.9			6.329		
Center target	−0.8	−4.20	.000			
Center Target × Age 8	—	—	—			
Center Target × Age 9	—	—	—			
Center Target × Age 10	1.4	2.64	.004			
Center Target × Preterm	—	—	—			
Center Target × Age 8 × Preterm	—	—	—			
Center Target × Age 9 × Preterm	—	—	—			
Center Target × Age 10 × Preterm	—	—	—			
Far target	−0.5	−2.43	.008	**0.064**	**3.47**	**.000**
Far Target × Age 8	—	—	—	**−0.081**	**−2.36**	**.009**
Far Target × Age 9	—	—	—	—	—	—
Far Target × Age 10	1.6	3.07	.001	−0.070	−1.43	.08
Far Target × Preterm				−0.042	−1.52	.06
Far Target × Age 8 × Preterm	—	—	—	0.049	0.93	.18
Far Target × Age 9 × Preterm	—	—	—	—	—	—
Far Target × Age 10 × Preterm	—	—	—	0.072	1.12	.13
Age 8	—	—	—	**−0.133**	**−1.89**	**.03**
Age 9	−0.9	−2.46	.008	**−0.219**	**−3.75**	**.000**
Age 10	−1.2	−2.19	.02	**−0.385**	**−4.50**	**.000**
Preterm	0.3	0.71	.24	−0.019	−0.31	.38
Preterm × Age 8	—	—	—	0.112	1.30	.10
Preterm × Age 9	2.4	2.01	.02	**0.160**	**2.21**	**.01**
Preterm × Age 10	—	—	—	−0.037	−0.36	.36

Note. Values in bold are significant at $p \leq .05$, and the effect size was larger than criterion. Dashes indicate that the term was removed from the model. For DT, the cells for center target are blank because this target was not presented.

crease in target distance results in an increase in the parameter. For PE, the likelihood ratio in the categorical model was significantly lower than in the interval model, $\chi^2(8) = 17.59$, $p = .03$. Consequently, all tests for RT, MT, ACCT, and DECT were performed using the simplified interval models shown in Table 3, and all tests for PE were performed using the simplified categorical model shown in Table 4. The simplified categorical model for DT is also shown in Table 4. The estimated means of all dependent variables for each age category in the two groups are shown in Figure 2 (pointing task) and Figure 3 (visual–perceptual control task).

Effect of Prematurity: Movement Programming Phase

Mean RT in the preterm group was significantly longer than in the control group at 7 years, $t(92) = 1.93$, $p = .03$, and at 9 years, $\chi^2(1) = 4.21$, $p = .04$ (see Figure 2).

Effect of Prematurity: Movement Execution Phase

At 7, 9, and 10 years, mean MTs in the preterm group were significantly longer than in the control group, $t(94) = 2.68$, $p = .004$, for each age group (see Figure 2). Note that a single *t* test covers all contrasts because the interaction effects of preterm by 9 years and preterm by 10 years could be removed (see Table 3). This effect could not be attributed to outliers (> 2 *SD*s above the mean).

At 7 and 9 years, mean ACCTs in the preterm group were significantly longer than in the control group, $t(94) = 1.93$, $p = .03$, for each age group. Note that a single *t* test covers the two contrasts because the interaction effect of preterm by 9 years could be removed (see Table 3). Mean DECTs did not differ significantly between the two groups at any age.

At 9 years, mean PE in the preterm group was significantly greater than in the control group, $\chi^2(1) = 5.96$, $p = .02$.

Effect of Age in the Control Group: Movement Execution Phase

At 9 years, mean MT was significantly longer than in 10-year-olds, $\chi^2(1) = 3.83$, $p = .05$.

Mean ACCTs in 7- and 9-year-olds were significantly shorter than in 8-year-olds, $t(94) = 1.69$, $p = .05$, for each age group comparison. Because 9-year-old control children did not differ from 7-year-old control children (see Table 3), the intercept represents both the 7- and 9-year-old control children. Consequently, one *t* test is sufficient to test differences with 7- and 9-year-old control children. Mean ACCT in 10-year-olds was significantly shorter than in 9-year-olds, $t(94) = 1.71$, $p = .05$. Mean DECT did not differ significantly between consecutive age groups.

Mean PEs were significantly smaller in 9- and 10-year-olds than in 7- and 8-year-olds, $t(95) = 2.46$, $p = .008$, compared with 9-year-olds, and $t(95) = 2.19$, $p = .02$, compared with 10-year-olds. Because 8-year-old control children did not differ from 7-year-old control children (see Table 4), one *t* test is sufficient to

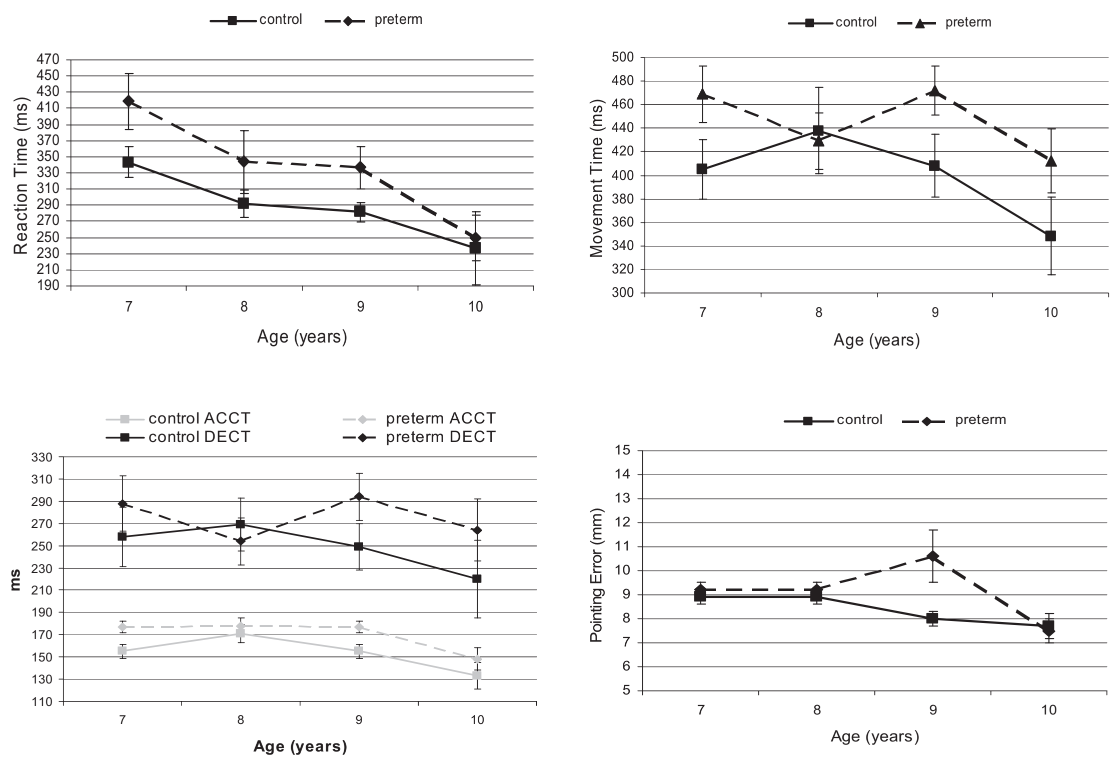

Figure 2. Mean and standard error (error bars) of reaction time (top left), movement time (top right), acceleration time (ACCT; gray), and deceleration time (DECT; black; bottom left), and pointing error (bottom right) for each age category in the two groups.

test differences with 7- and 8-year-old control children. However, all differences between the age groups were less than 2 mm.

Effect of Age in the Preterm Group: Movement Execution Phase

Mean MT in 10-year-olds was significantly shorter than in 9-year-olds, $\chi^2(1) = 3.83$, $p = .05$ (see Figure 2).

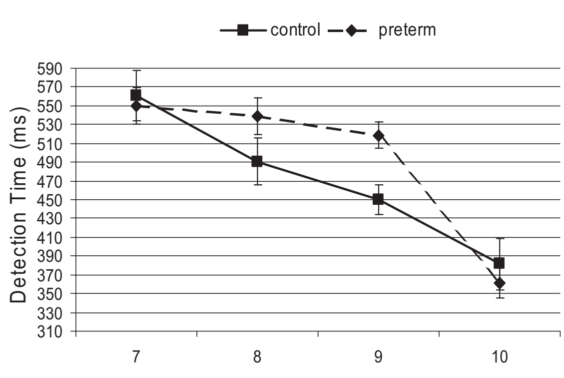

Figure 3. Mean and standard error (error bars) detection time for each age category in the two groups on the visual–perceptual control task.

Mean ACCT in 10-year-olds was significantly shorter than in 9-year-olds, $\chi^2(1) = 7.07$, $p = .008$. Mean DECT did not differ significantly between consecutive age groups.

Mean PE was both significantly larger in 9-year-olds than in 10-year-olds, $\chi^2(1) = 4.76$, $p = .03$, and relevant (3 mm).

Detection Time

At 9 years, mean DT was significantly longer in the preterm group than in the control group, $\chi^2(1) = 10.03$, $p = .002$ (see Figure 3).

Discussion

Our investigation of pointing movements in a group of 7- to 10-year-old preterm-born children without CP and an age-matched full-term group found slower reaction, movement, and acceleration times in the preterm group, with no gain in endpoint accuracy, suggesting that elementary visuomotor processes were less efficient in this group. The findings and their implications for dorsal visual stream and cerebellar functioning are discussed below.

Impairment of Dorsal Visual Stream and/or Cerebellar Functioning?

Reaction times provide information on the speed of transforming visuospatial information into motor parameters, a function of the dorsal visual stream (Milner & Goodale, 1995). Because no sensory feedback processing occurs during movement programming, RTs do not provide information on the functioning of the cerebellum, which is involved in online movement control on the basis of sensory feedback processing (Blakemore et al., 2001). The longer RTs in the preterm group at 7 and 9 years of age then suggest that movement programming processes are slower in children born preterm than in typically developing children. This is consistent with an impairment of dorsal visual stream functioning in these children.

If dorsal visual stream functioning is impaired, then not only movement programming but also movement execution should be slower. The acceleration phase, which reflects the accuracy of movement programming, reflects the efficiency of dorsal stream functioning particularly well. The deceleration phase may also reflect dorsal stream functioning because visual information has to be transformed rapidly into motor parameters to control the ongoing movement during this phase (Milner & Goodale, 1995). Movement execution was slower in the 7-, 9-, and 10-year-old preterm groups. Acceleration time was longer in the 7- and 9-year-old preterm groups. Deceleration time was substantially longer (12% to 20%) in the 7-, 9-, and 10-year-old preterm groups, although the differences did not reach significance, probably as a result of the large interindividual differences in both groups in this particularly complex phase of the movement (Elliott et al., 1999). The slower movements in the preterm group could not be attributed to differences in speed–accuracy trade-off because their accuracy was similar to or less than that of the control group at all ages. Overall, these results are consistent with impaired dorsal stream functioning in preterm-born children.

As described in the introduction, there is evidence for impaired dorsal stream functioning accompanied by intact ventral stream functioning in preterm-born children. Similar differences in visual functioning have been found in other atypically developing groups of children (Atkinson, 2000). This suggests that the dorsal visual stream is more vulnerable than the ventral visual stream to early disruption. The mechanisms underlying this vulnerability are as yet unclear. In preterm-born children, they may be related to premature stimulation of an immature visual system or to a high sensitivity for minor organic damage. However, longer movement and deceleration times may also reflect impaired cerebellar functioning given that the cerebellum is involved in dynamic feedforward motor control, which is part of the online motor control system. Impaired cerebellar growth has been reported in preterm-born children (Allin et al., 2001; Limperopoulos et al., 2005). The mechanisms underlying such impaired growth are poorly understood, but may include impairment secondary to white matter injury (Shah et al., 2006).

In conclusion, the findings of both slower movement programming and movement execution in the preterm-born group indicate an impairment of dorsal visual stream functioning in preterm-born children without CP. However, impaired cerebellar functioning may also be involved in the slower movement execution.

It is important to note that the longer RTs in the preterm group were not part of a general slowing in information processing. Mean DT on a visual–perceptual control task was longer at 9 years in the preterm group (see Figure 3), whereas mean RTs were longer at 7 and 9 years. Given the similar detection times between the preterm and control groups at 7 years, it is unlikely that the longer mean RT in the 9-year-old preterm group reflects only generalized slowing. Rather, both generalized slowing in information processing and specific slowing of movement programming seem to be implicated in the 9-year-old preterm group.

It is interesting that, at 8 years of age, we found no differences between the two groups in MT, ACCT, or DECT. As expected, these movement execution parameters did not decrease linearly in the control group. Between 7 and 8 years of age, MT actually increased, although not significantly, whereas ACCT increased significantly. This is consistent with the literature, which has shown a transition in the development of movement control, associated with slower movements, around 8 years of age (Chicoine et al., 1992; Ferrel et al., 2001; van Dellen & Kalverboer, 1984). In contrast, both MT and DECT decreased between 7 and 8 years in the preterm group, although the decreases were not significant. The approximately equal MTs, ACCTs, and DECTs in the 8-year-old control and preterm groups therefore may reflect the occurrence of a transition in the development of movement control in the control group but not in the 8-year-old preterm group. A longitudinal study would provide more convincing evidence for this interpretation.

Limitations of the Study

Neither dorsal visual stream nor cerebellar functioning was measured directly in this study. Imaging these networks is the next logical step in testing our hypothesis. The two groups were not matched on intelligence. The preterm group had significantly lower IQs than the control group. However, we find it unlikely that IQ can explain differences between the preterm and control groups on a simple visuomotor task in which high-level cognition has minimal influence.

Theoretical and Clinical Implications

Research into the sequelae of serious prenatal lesions or insults sustained during the 1st year of life has shown that there are limitations to the plasticity of the young human brain (Anderson et al., 1997; Riva & Cassaniga, 1986). The preterm-born children studied here had survived severe prematurity without developing CP. The visuomotor processes required for the pointing task had received daily practice over a number of years. However, these children still performed less efficiently on a simple visuomotor task. The differences we found, although small, add to our understanding of plasticity by suggesting that there are limitations to the plasticity of the young human brain in children with atypical early medical histories, even in the absence of serious perinatal brain injuries.

From a clinical perspective, this study suggests that parents and teachers of preterm-born children without CP should be alert to subtle deficits in elementary visuomotor processes, which could interfere with the acquisition of important daily life skills such as writing, lacing shoes, and fastening buttons.

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